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WHEATSTONE BRIDGE SCHEME FOR SENSOR

[0001] Prior attempts to form a Wheatstone Bridge for use in nano scale biological or chemical sensors have resulted in arrangements which have suffered from shortcomings such as there being no offset cancellation at the input stage, the dynamic range of the circuit being reduced, a lower power supply noise rejection ratio (PSRR) resulting, and/or it being detrimentally affected by temperature.

BRIEF DESCRIPTION OF THE DRAWINGS

[0002] Fig. 1 is a schematic depiction of a Wheatstone Bridge.

[0003] Fig. 2 is a schematic depiction of a nano wire Wheatstone Bridge implementation of a Wheatstone Bridge.

[0004] Fig. 3 is a plan view of a full Wheatstone Bridge constructed using nano wires.

[0005] Figs. 4-8 are views depicting the steps which are involved in the fabrication of a Wheatstone Bridge.

[0006] Fig. 9 is a schematic layout showing a centroid arrangement via which linear fabrication process variations can be compensated for.

[0007] Fig. 10 is a schematic layout similar to that shown in Fig. 9 showing a variant of the centroid arrangement depicted therein.

[0008] Fig. 11 is a schematic layer showing a further centroid layout arrangement via which fabrication process variations can be compensated for.

[0009] Fig. 12 is a sectional view showing an embodiment of the invention wherein an appropriate bias is applied to the substrate to negate average imbalance between the sensor elements.

[0010] Fig. 13 is a top plan view showing an embodiment of the invention wherein the bridge is electrically trimmed by gating the nano wires to produce an arrangement via which balance can be actively achieved.

[0011] Fig. 14 is a side view of the arrangement shown in Fig. 13 as taken along section line XII - XII.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS

[0012] The embodiments of the invention relate to but not limited to nano scale semiconductor type field-effect sensors including biological and chemical sensors. In these type of semiconductor sensors which are fabricated to include nano-scale wires, a suitable coating or arrangement is provided over the wires which reacts or responds to a given biological or chemical agent that is allowed to come in contact with the coating/arrangement. This coating/arrangement responds by generating a sensible stimulus in the form of the attachment of species on the sensor surface which change the nanowire surface potential and hence the conductance of the nano wires. By sensing the change in the conductance of the nano wires it is possible to sense whether or not certain biological or chemical agents are present.

[0013] Inasmuch as these nano wire sensor elements are, in accordance with the embodiments of the invention, elements of a Wheatstone bridge circuit, they are, in addition to being configurable as chemical and biological sensors, also adaptable to respond to other stimuli such as photons and magnetic fields. The scope of application of the embodiments is not limited to the above mentioned applications and the various other possibilities will become evident as the disclosure of the embodiments unfolds.

[0014] A full Wheatstone bridge circuit includes four resistive components (R1, R2, R3 and R4). These resistive components are connected so as to establish

junctions A, B, C and D. Further, as show in Fig. 1, these resistive components are connected with a voltage source V_{in} across junctions A and C and voltmeter V_g which measures the voltage which is developed across junctions B and D.

[0015] The up/down sense of the arrows in this figure indicate the direction of response to external stimulus. The circuit effectively adds the differential outputs of R1-R4 and R2-R3. By using all of the resistances R1, R2, R3 and R4 as sensing elements and arranging R1 and R3 to react to the same stimulus in the opposite way to R2 and R4, it is possible with the embodiments of the invention, to provide a gain of 4 without adding amplification noise.

[0016] The embodiments of the invention implement a full Wheatstone Bridge by using P type and N type semiconductor nano wires as the resistances R1, R2, R3 and R4 in the manner depicted in Fig. 2. The semiconductor materials used to form the nano wires can be of any suitable semiconductor material such as silicon, germanium, diamond, SiC, Si-Ge alloy, GaAs, other III-V compounds, GaN, other II-VI compounds, SnO, or other metal oxide semiconducting materials.

[0017] In Fig. 2 numerals 101 – 104 denote low resistance connection elements, such as metallic layers/lines, which are arranged to provide low resistance connections between the nano wires and thus respectively function as the connections B, C, D and A shown in Fig. 1. In the embodiments of the invention, each of the nano wires comprise an elongated, nano width doped region formed on a suitable insulating layer, such as silicon oxide, which is formed on a suitable substrate, such as silicon.

[0018] In the embodiments of the invention, the nano wires are all adapted to respond to a stimulus such as the application of a chemical or biological agent (merely by way of example) to a sensing coating and/or arrangement (not shown) which is suitably disposed with the wires. The interaction between the coating/arrangement and the agent induces the P type wires to increase resistance with a positive charge and N type wires to react by decreasing

resistance with the same charge. This achieves the above mentioned gain of 4 without adding amplification noise.

[0019] With this type of arrangement it is desirable that the bridge assume a balanced state prior to being exposed to a sample. An ideally balanced bridge has all four resistances equal, i.e., $R1 = R2 = R3 = R4$ so that it produces a zero reading when there is no stimulation. That is to say, for a resistive measurement, it is desirable to have a balanced bridge, whether it is a full bridge, half or even a quarter bridge.

[0020] Embodiments of the present invention are effective in a balanced full Wheatstone Bridge configuration, as described above, wherein the four resistor elements are chemically sensitive and are deployed as two pairs of substantially identical resistors, $R1$ & $R3$ and $R2$ & $R4$, and wherein the pairs are doped differently so as to respond oppositely to the same stimulus (as in Fig. 1). Embodiments of the invention can also be configured as a balanced half Wheatstone bridge in which only one pair of substantially identical resistors ($R1$ & $R3$) respond to the stimulus in the same direction and resistors $R2$ & $R4$ are not responsive to the stimulus. Embodiments of the invention can also be configured as a balanced quarter Wheatstone bridge in which only one resistor, $R1$, is responsive to the stimulus and resistors $R2$, $R3$, and $R4$ are not responsive.

[0021] In the above-mentioned embodiments the balanced full Wheatstone bridge is comprised of nanoscale resistor elements, $R1 - R4$. However, embodiments of the invention can be implemented entirely or partly of microscale resistor elements which are sensitive to external stimulus. The balanced quarter and half Wheatstone bridge embodiments of the present invention can also be comprised of nanoscale resistor elements and microscale resistor elements having the desired balance and response to external stimulus, as described above.

[0022] Fig. 3 is a schematic plan view of a nano-wire Wheatstone Bridge. In this figure, resistances R1, R2, R3 and R4 are interconnected by the metallic connectors 101 - 104 in the same manner shown in Fig. 2.

[0023] Figs. 4-8 depict a process via which the arrangement shown in Fig. 3 can be fabricated. Fig. 4 shows a wafer 150 on which a layer of silicon 152 suitable for doping has been prepared. Fig. 5 shows a first P type nano wire (viz., an elongated nano width region) 154 which is produced using a suitable masking and doping technique such as ion implantation or the like. Fig. 6 shows a second nano wire 156, which in this instance is a N type doped wire (viz., an elongated nano width region) formed in a predetermined spatial relationship with the first wire.

[0024] After the superfluous material has been removed such as by etching (Fig. 7) the remaining nano-wires 152, 154 are electrically connected by metallization and patterning (Fig. 8) schematically depicted at 158. In that these techniques are well known in the art of semiconductor fabrication inclusive of the doping concentrations, doping agents, etchants, photolithographic materials, and nano patterning, etc. which are used, and the various alternative ways in which they can be used, no further disclosure will be given for the sake of brevity.

[0025] However, with nano-scale production a minor process variation may have a large impact on the characteristics of the nano scale wires. That is to say, during fabrication it is inevitable that there is some variation (e.g. process variation) in the width (or other parameter) of the wire. However, because the embodiments of the invention are fabricated on the nano scale as different from a micron scale (wherein variation tends to be at the lower end of the micron scale), the impact of any variation in the nano scale represents a large percentage deviation and therefore has a very large effect on the resistance value of the nano wires, even to the degree that the sensor sensitivity could be overwhelmed.

[0026] As noted above, in the case of a full Wheatstone bridge, the resistance of the two P type resistors need to be identical and the resistance of the two N

type resistor need to be identical. Fig. 9 shows a nano-wire fabrication layout which attenuates the effect of a possible linear variation due to fabrication process variation by enabling resistance matching. This layout improves the bridge balance by using a common centroid about which the nano wires are disposed and thus arranges the wires so that the linear variation in the fabrication process is shared in a manner which induces a mutual balancing effect.

[0027] Fig. 9 shows a situation wherein two nano wires in one arm of the bridge shown in Fig. 2, which comprise substantially equivalent resistances R_1 and R_4 for example, are each formed in two halves, viz., R_{1A} and R_{1B} , and R_{4A} and R_{4B} . R_{1A} and R_{1B} are fabricated collinearly to R_{4A} and R_{4B} and such that their centroids are identical. Because the resistor halves are collinear with a common centroid, any differences in two halves R_{1A} and R_{1B} due to a linear process variation will be very similar to that on the halves R_{4A} and R_{4B} so that the resistances of R_1 and R_4 will therefore exhibit essentially similar characteristics and the possible detrimental effects of linear process variation will be compensated.

[0028] Fig. 10 shows the situation wherein each of the resistances $R_1 - R_4$ is formed as two halves wherein each is designated with the suffix A or B. By forming the two halves and four resistances in a corresponding spatial relationship with the common centroid the effect of one or more linear variations during fabrication can be compensated and the resistances of each resistor formed by nano wires can be equalized.

[0029] Common centroid layout techniques can be realized with more than two identical sub units. Fig. 11 shows the situation wherein each of the resistances $R_1 - R_4$ is consisted of three sub units wherein each is designated with the suffix A, B or C. What is not shown is the low resistance path to connect these three sub units together to form one resistor. By forming the three sub units essentially equidistant from and about a centroid and four resistances in a corresponding spatial relationship with the common centroid the effect of one or

more linear variations during fabrication can be compensated and the resistances of each of resistors can be equalized.

[0030] The common centroid layout technique is particularly effective in compensating for linear process variations. There are instances wherein non-linear process variations cannot be adequately compensated, for example, when the variations are due to differences in the N-doped and P-doped regions. In these situations it is possible to gate the wires, in order to adjust their resistance and to balance the circuit. Gating the semiconducting wires may be done via an applied electric field.

[0031] Fig. 12 is a side-view depiction of an appropriate embodiment as an extension of Figs. 3 and 8. In Fig. 12, the substrate 150 is structured so as to present an electric field to the wires 154 and 156, for instance by the substrate comprising a thin insulating layer 159 and a conducting underlayer that can be contacted electrically by a conducting element 160. A convenient way to fabricate such a structure employs a silicon-on-insulator starting wafer though other methods can also be used. In Fig. 12, note that a positive gating field will tend to decrease resistance in N-doped wires and increase resistance in P-doped wires, whereas a negative gating field will do the opposite. This embodiment of gating the P and N-doped wires via the common substrate potential is therefore particularly well adapted to balancing P-type and N-type Wheatstone bridge circuits where doping variation may require compensation.

[0032] Individual wires can be gated to balance the Wheatstone bridge circuit, as shown in Figs. 12 and 13. Here, a gate is provided on top of a section of a wire and is separated from it by a thin dielectric layer, such as 10-nm thick, thermally grown silicon dioxide. In accordance with this embodiment, the wires 200p, 200n are each provided with one or more gates. In the arrangement shown in Figs. 12 and 13, the nano-wires 200p, 200n respectively have gates 200pG, 200nG associated therewith. Each of these gates 200pG, 200nG comprises an electrically conductive layer (such as metal) which is separated from the nano wire by an insulating oxide film 210.

[0033] The ends of the wires are shown electrically connected to connector elements 220 which are made of a highly conductive material such as aluminum or the like. Although only two wires are shown it will be understood that more can be formed and that the connector elements, although here not illustrated as doing so, are suitably connected with other elements to form a bridge circuit.

[0034] As shown in Fig. 14, the gates are electrically connected via suitable wiring to an interface. This interface is connected with a voltage control circuit which is responsive to the output of the bridge circuit and which is capable of selectively applying a suitable voltage to one or more of the gates to bring the bridge into balance. This process would typically be carried out during sensor initialization/calibration wherein the output is adjusted prior to the sensor being exposed to a sample requiring measurement.

[0035] As noted above, a common centroid layout configuration of the Wheatstone sensors is effective in compensating for linear process variations. It is further noted that a common centroid layout may also be used to improve the performance of the Wheatstone bridge in some specific applications or environments where non-process variations may occur.

[0036] For example, a Wheatstone bridge according to one embodiment of the invention may have a common centroid layout configuration and may be used for biological and/or chemical sensing within micro/ Nano-fluidic systems. That is to say, the common centroid layout may compensate for certain variations with the fluidic system, such as in the case of sensor elements that are positioned near the boundary of a flow region. This may be useful in lab-on-a-chip and other applications of integrated fluidics. In another embodiment, the balanced Wheatstone bridge is used to adapt to linear variations in a flowing stream along the flow direction.

[0037] Although the invention has been disclosed with reference to only a limited number of embodiments, it will be appreciated that the scope of the invention, which is limited only by the appended claims, is not restricted to these specific examples and that various modifications and changes, which will be self-

evident to the person skill in the art to which the present invention is applicable given the preceding disclosure, can be implemented without undue experimentation.